# Atomic physics experiments with trapped and cooled highly charged ions

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**Abstract.** Trapping and cooling techniques have become very important for many fundamental experiments in atomic physics. When applied to highly charged ions confined in Penning traps, these procedures are very effective for testing quantum electrodynamics in extreme electromagnetic fields produced by heavy highly charged ions such as uranium $U^{91+}$. In addition, fundamental constants or nuclear ground state properties can be determined with high accuracy in these simple systems. Finally, by studying a single trapped radioactive ion, its nuclear decay can be studied in detail by observing the disappearance of the signal of the mother and the appearance of that of the daughter isotope. Such experiments on highly charged ions at extremely low energy will become possible by the HITRAP facility which is currently being built up at GSI. Also the future Facility for Antiproton and Ion Research (FAIR) will be briefly described which is expected to be operational by 2014.

## 1. Why use highly charged ions?

Quantum electrodynamics (QED) is the most precisely investigated theory in physics [1]. It describes the interaction of electric charges by exchange of photons, and serves as a basis for many other existing field theories. Experimental studies have been carried out with extremely high precision of up to $10^{-14}$, always consistent with the QED predictions. For a few simple systems, the experimental accuracy is matched by nearly equally exact theoretical calculations, which shows the power of the underlying mathematical framework. Discrepancies between theory and experiment are nowadays often caused by insufficient knowledge of the nuclear size and its structure. Even fundamental constants are known to limit the predictive power of QED to a certain extent. This, however, allowed high-accuracy experiments to provide the most precise values for the fine-structure constant $\alpha$ [2] and the mass of the electron $m_e$ [3].

For such precision studies, simple systems have to be investigated, consisting of just an atomic nucleus and a few electrons at most. Few-electron systems with a heavy nucleus are particularly important because they allow one to access the regime of extreme electromagnetic fields ($\approx 10^{16}$ V/cm) within a range of distances of the order of the electron's Compton wavelength. This is also the region where perturbative QED, although being very precise, breaks down [4]. The energy contained in these fields is also very close to that required for the spontaneous creation of an electron-positron pair out of the vacuum (Schwinger-limit).

Highly charged ions (HCI), combining very strong static fields and a simple electronic structure, are ideal testing grounds for these high-field QED investigations. HCI can readily be produced and stored in traps and rings. Sensitive techniques, such as mass or laser spectroscopy in storage rings, ion traps, and electron beam ion traps, have been developed to further advance this field. However, experiments with heavy HCI have not (yet) matched the accuracy of experiments performed with hydrogen or simple light systems, *e.g.*, the free electron or positronium.

HCI are either produced at once by impact of an energetic ion beam on a 'stripper target', or stepwise by electron impact ionisation of trapped ions. Presently, the only way to produce sufficient amounts of HCI (up to $U^{91+}$) is by using relativistic ion beams (about 1 GeV per nucleon) in combination with a stripper target, as being done at GSI.

## 2. Experiments with trapped and cooled highly charged ions

In a Penning trap, charged particles are confined in the axial or $z$-direction by an electric quadrupole field created by applying static potentials ($\sim 10$ V) to the trap electrodes, which typically consist of two endcaps and one ring electrode [5]. In the radial or $xy$-plane, confinement is generally achieved by use of a superconducting magnet which provides a strong, stable, and homogeneous static magnetic field. The motions that the trapped particles undergo are all simple harmonic oscillations and are very well under control. The motion in the $z$-direction is an oscillation with the axial frequency $\omega_z$, and is the simplest motion to cool and to detect. In the radial plane there are two circular motions: a fast motion with the modified cyclotron frequency $\omega_+$, and a slow drift motion about the centre of the trap with the magnetron frequency $\omega_-$. The radiofrequency or Paul trap is another type of trap for charged particle confinement, which is very often used, but its description is beyond the scope of this paper.

Trapped (charged) particles form a point-like source and generally have small amplitudes of oscillation. Once trapped, the particles can easily be manipulated, $(q/m)$-selected, accumulated, and even polarized (*e.g.*, by optical pumping). A number of cooling techniques exist, which, besides removing the particles' kinetic energy and thus reducing Doppler effects, also improve particle manipulation, selection, and the resolution of the measurement. Such cooling techniques are laser cooling, sympathetic cooling, evaporative cooling, resistive cooling, and electron cooling. Cold ensembles of trapped particles can also be formed into dense crystalline ion structures which could, for example, lead to an enhanced luminosity for reaction studies. Since confinement times
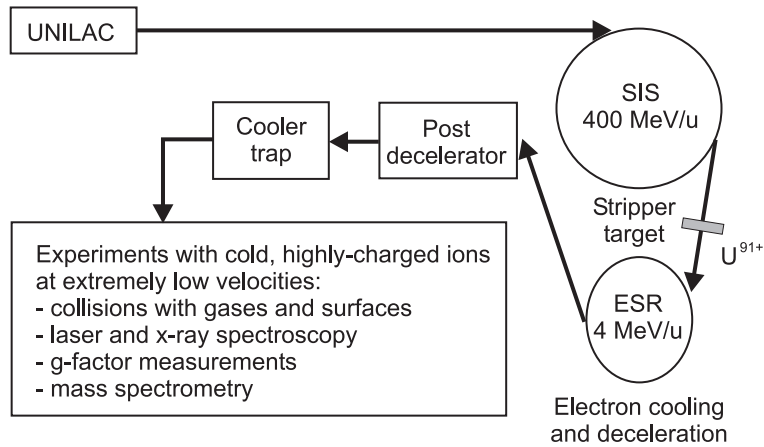


**Figure 1.** Schematic of the HITRAP project: deceleration, trapping, and cooling of highly charged ions for many key atomic physics experiments.

of trapped particles can indeed be very long (up to months), there is an extended observation and manipulation time. Thus metastable states can simply be eliminated by waiting, and a backing-free sample for decay studies can be obtained. This also makes traps very suitable for effective studies of rare species. Further applications are bunching, charge breeding, and post-acceleration. All the above mentioned methods lead to drastically increased efficiency, accuracy and sensitivity. In principle, the highest accuracy can be obtained when only a single (cold, highly charged) ion is used. Trapped highly charged ions have been successfully used for high-accuracy mass measurements in Seattle and Stockholm, for producing and studying ionic crystals in Livermore, and for the determination of the $g$-factor of the bound electron in hydrogen-like ions in a GSI-Mainz cooperation (see below).

In order to further increase the accuracy, the Highly charged Ion TRAP (HITRAP) facility is presently being built at GSI, and will be operational in 2008 [6]. Briefly, stable or radioactive HCI at relativistic velocities (400 MeV/u) are decelerated (and cooled) in the experimental storage ring (ESR) down to 4 MeV per nucleon, and injected into the HITRAP facility. Here, they will be further decelerated by a linear decelerator and a radiofrequency quadrupole structure (RFQ), and injected into a cooler Penning trap, where a temperature of 4 K is reached by electron and resistive cooling. The cold HCI are then transferred at low energies (5 keV per charge) through a beamline to different experimental setups. The planned unique experiments are being prepared by several international groups (GANIL, Groningen, GSI, Heidelberg, Krakow, London, Mainz, Stockholm, and Vienna) within the EU-funded HITRAP project. A schematic of HITRAP is shown in figure 1, together with a list of some planned atomic physics experiments. Below, two such experiments are described in some more detail.

### 2.1. Laser spectroscopy

The ground-state hyperfine splitting (HFS) of heavy H-like ions increases with the nuclear as $Z^3$ and enters the laser-accessible regime for heavy elements such as $^{207}\text{Pb}^{81+}$ or $^{209}\text{Bi}^{82+}$. The $1s$ HFS in these H-like systems has been studied at the ESR storage ring at GSI by collinear laser spectroscopy [7, 8], and at the SuperEBIT in Livermore [9, 10, 11, 12]. There also exist two measurements of the $2s$ ground state HFS in Li-like bismuth ($^{209}\text{Bi}^{80+}$). A direct measurement [13] was carried out at the ESR, but unfortunately no resonance could be observed at the
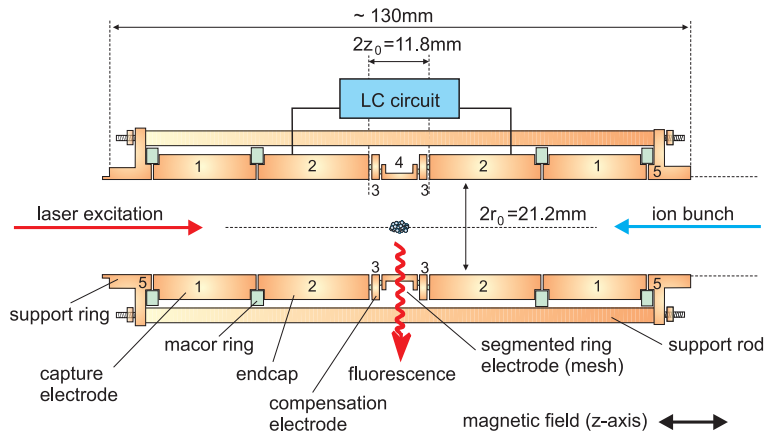


**Figure 2.** Schematic of the Penning trap that will be used to measure ground-state hyperfine splittings in highly charged ions. The ions come from the right, are trapped, cooled and compressed, and are excited by a laser beam from the left. The emitted fluorescence is detected through the optically transparent ring electrode.

predicted value of $\approx 1554$ nm [14]. The reason is unknown. An indirect measurement [15] was performed in the SuperEBIT and yielded a value of $\approx 1512$ nm, but the error in the measurement was rather large ($\approx 50$ nm). From a comparison of the HFS of a H- and a Li-like system, the nuclear effects (*e.g.*, Bohr-Weisskopf) cancel out to a large extent, and the QED effects can be determined within a few percent accuracy [14, 16]. Furthermore, if the nuclear magnetic moments $\mu$ are not very well known, HFS measurements in few-electron systems will also allow for a determination of $\mu$ and can thus help to improve the knowledge of nuclear properties.

For these laser experiments at HITRAP a cylindrical open-endcap Penning trap [17] will be mounted inside the cold (4 K) bore of a superconducting magnet (RETRAP [18]) with radial and axial access. RETRAP was previously used to trap $Xe^{44+}$ ions, produced by an electron beam ion trap, and to study the formation of ion crystals by sympathetic cooling with laser-cooled $Be^+$ ions [18]. The planned HFS laser measurements at HITRAP will take place within an international collaboration formed by GSI, Imperial College London, TU Darmstadt, Lawrence Berkeley and Livermore Labs, and Texas A&M University.

*2.2. Mass spectrometry*
The masses of stable or radioactive nuclides can be measured by Penning traps with very high accuracy and single-ion sensitivity [19, 5]. Since the cyclotron frequency of an ion in a Penning trap increases with the charge state, HCI provide better resolution and potentially also higher accuracy than singly charged ions. The SMILETRAP group at Stockholm has pioneered the use of HCI in ion traps for mass spectrometry [20, 21, 22] and measured with an uncertainty close to $10^{-10}$ the masses of several ions, which are important for fundamental tests of QED or double-beta decay. Using the mass of $^{12}C^{6+}$, the masses of singly charged stable ions have been measured with an accuracy of about $10^{-10}$ in Seattle by Van Dyck *et al.* [23]. The group of Gabrielse achieved a similar accuracy in the case of the proton-antiproton comparison at CERN [24]. An even better accuracy of about $10^{-11}$ was obtained at MIT by Pritchard *et al.* [25] with a mass spectrometer now at Florida State University [26]. The masses of singly charged radionuclides have been measured with an accuracy in the range of $10^{-7}$ to $10^{-8}$ and
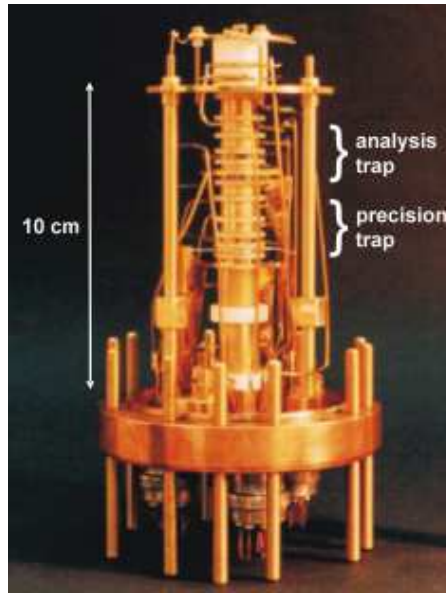


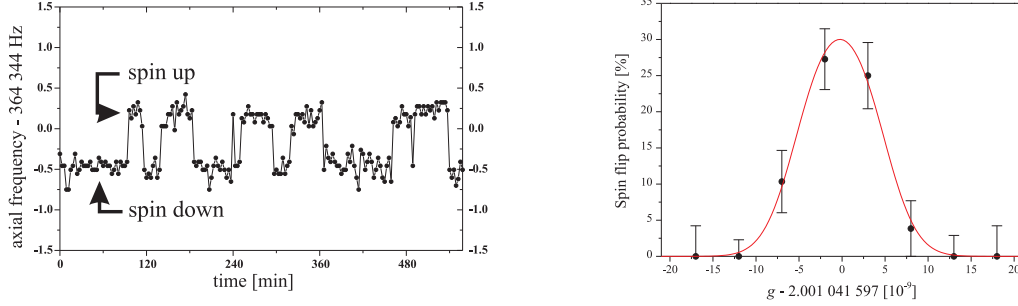**Figure 3.** Photograph of the GSI-Mainz *g*-factor Penning trap.

**Figure 4.** Result of the $g$-factor measurement of the bound electron in $^{12}C^{5+}$ [37]. The left panel shows individual spin-flips, the right panel the Larmor resonance.

better by Penning trap mass spectrometers installed at ISOLDE/CERN [27], Argonne [28], Jyväskylä [29], MSU [30], and GSI [31]. HCI for mass spectrometry will be used at TITAN at ISAC/TRIUMF, Vancouver [32], LEBIT/MSU [33], HITRAP/GSI [34], ISOLTRAP/ISOLDE [35], MAFFTRAP/Munich [36], and at MATS/Darmstadt [5].

A sensitive test of bound-state QED in strong fields is the measurement of the $g$-factor of the electron bound to a nucleus in a hydrogen-like ion. The ratio of the bound-electron ($g_{bound}$) to the free-electron g-factor ($g_{free}$) can be expressed to leading order in $Z\alpha$ as

$$\frac{g_{bound}}{g_{free}} \approx 1 - \frac{1}{3}(Z\alpha)^2 + \frac{1}{4\pi}\alpha(Z\alpha)^2, \tag{1}$$

where the second term stems from Dirac theory and the third from bound-state QED.

Within the Mainz-GSI collaboration, the $g$-factor of the bound electron in $^{12}C^{5+}$ [37] and $^{16}O^{7+}$ [38] has been obtained via spin-flip measurements of a single cold (4 K) ion. The setup consists of two Penning traps [39], *i.e.* a 'precision trap' and an 'analysis trap', in one superconducting magnet. Figure 3 shows a photograph of the Penning trap. The $g$-factor can be obtained from measurements of the cyclotron frequency $\omega_c = qB/M_{ion}$ and the Larmor frequency $\omega_L = geB/(2m_e)$, as it can be expressed as

$$g = 2\left(\frac{q}{e}\right)\left(\frac{m_e}{M_{ion}}\right)\left(\frac{\omega_L}{\omega_c}\right), \tag{2}$$

where $m_e, e$ and $M_{ion}, q$, are the mass and charge of the electron and the ion, respectively. The three oscillation frequencies of an ion inside a Penning trap can be measured independently and with high accuracy, using resonant circuits with high quality factors. The polarisation of the electron spin was 100%, simply because only one ion was used. Inside the precision trap $\omega_c$ is determined, and a spin-flip may be induced by microwave irradiation at a frequency close to the spin precession frequency $\omega_L$. Detection of a spin-flip takes place after transporting the ion to the analysis trap. Here, a significant inhomogeneity of the magnetic field, produced by a nickel ring, makes the $z$-motion of the ion sensitive to the spin direction. The frequency of the $z$-motion is detected via the image charges induced in the endcap electrodes. After analyzing the spin direction, the ion is transported back and the next measurement cycle begins.

Figure 4 shows the experimental result obtained for a $g$-factor measurement of a single $^{12}C^{5+}$ ion. The abscissa indicates the measured Larmor precession frequency of the bound electron which directly yields, after dividing by the simultaneously measured ion cyclotron frequency, the $g$-factor of the bound electron. The experimental $g$-factors of the hydrogen-like ions $^{12}C^{5+}$

**Table 1.** Comparison of the accuracy of mass measurements as obtained for a singly and for a highly charged ion with mass number $A = 100$ in a magnetic field of $B = 6$ T. $\nu_c$ is the cyclotron frequency, $T_{obs}$ the observation time of a measurement, $R$ is the resolving power given by the ratio $\nu_c/\delta\nu_c$, and $\delta m/m$ is the mass uncertainty.

| singly charged ion | | highly charged ion | |
|---|---|---|---|
| $q = 1$ | $\nu_c = 1$ MHz | $q = 50$ | $\nu_c = 50$ MHz |
| $T_{obs} = 1$ s | $\delta\nu_c = 1$ Hz | $T_{obs} = 1$ s | $\delta\nu_c = 1$ Hz |
| $R = 10^6$ | $\delta m/m \approx 10^{-8}$ | $R = 5 \times 10^7$ | $\delta m/m \approx 2 \times 10^{-10}$ |

[37] and $^{16}O^{7+}$ [38] agree within the uncertainties, which are dominated by the accuracy of the electron mass, with the theoretical ones [1]. The $g$-factor found for the $1s$ electron in these systems enabled a test of bound-state QED on a 0.25% level. Because of the good agreement of these $g$-factors with theory, the data could be used to determine the electron mass four times more accurately than the previously accepted value [40]. The achieved experimental accuracy $\delta m_e/m_e$ of this measurement was as good as $6 \times 10^{-10}$.

In table 1, a comparison is made between a mass measurement using a singly charged ion in a Penning trap and one employing a highly charged ion. From the table it is clear that, for the same isotope, a HCI with a charge $q$ of, for example, 50 already leads to an improved mass resolution of nearly two orders of magnitude. Higher charge states (*i.e.* $q = 92$ for the case of uranium) and longer observation times (for example, $T_{obs} >= 10$ s) will improve the mass resolution even further and will make it possible to reach a mass measurement accuracy of $10^{-11}$ or better with highly charged ions. This would allow one to measure the $1s$ Lamb shift in hydrogen-like uranium by weighing with an accuracy better than by x-ray spectroscopy.

## 3. FAIR - the future Facility for Antiproton and Ion Research

In the more distant future, HITRAP will be a component of the Facility for Low-Energy Antiproton and Ion Research (FLAIR) at the future international accelerator facility FAIR [41]. There, HITRAP will not only provide low-energy highly charged stable or radioactive ions for experiments of the SPARC Collaboration, but also low-energy antiprotons. Furthermore, the FAIR facility will provide highest intensities of both stable and radioactive ion beams and energies up to 34 GeV per nucleon. At such energies, the HCI generate electric and magnetic fields of exceptional strength and ultra-short duration.

### 3.1. Stored Particle Atomic Research Collaboration (SPARC)

The new FAIR facility has key features that offer a range of new opportunities in atomic physics research and related fields, which will be exploited by the atomic physics Collaboration SPARC [42]. In particular, at FAIR the Super Fragment Separator (SFRS) will provide a rich spectrum of radionuclides that are not available at any other facility. The high intensity of secondary beams produced at the SFRS will make it possible to extract decelerated radioactive ion beams from the New Experimental Storage Ring (NESR) and to decelerate them for trap experiments with sufficient intensity at HITRAP. Therefore, the physics programme of HITRAP at FLAIR can be extended to novel experiments with trapped radioactive ions and, of course, with trapped antiprotons. Trapped radioactive ions in high charge states may reveal a completely new domain for fundamental interaction studies and for experiments at the borderline between atomic and nuclear physics.

Moreover, the manipulation of trapped radioactive ions with laser light opens up possibilities to study questions of the Standard Model of fundamental interactions in a unique way at HITRAP. By optical pumping within the hyperfine levels of the ground state, the nuclear spins
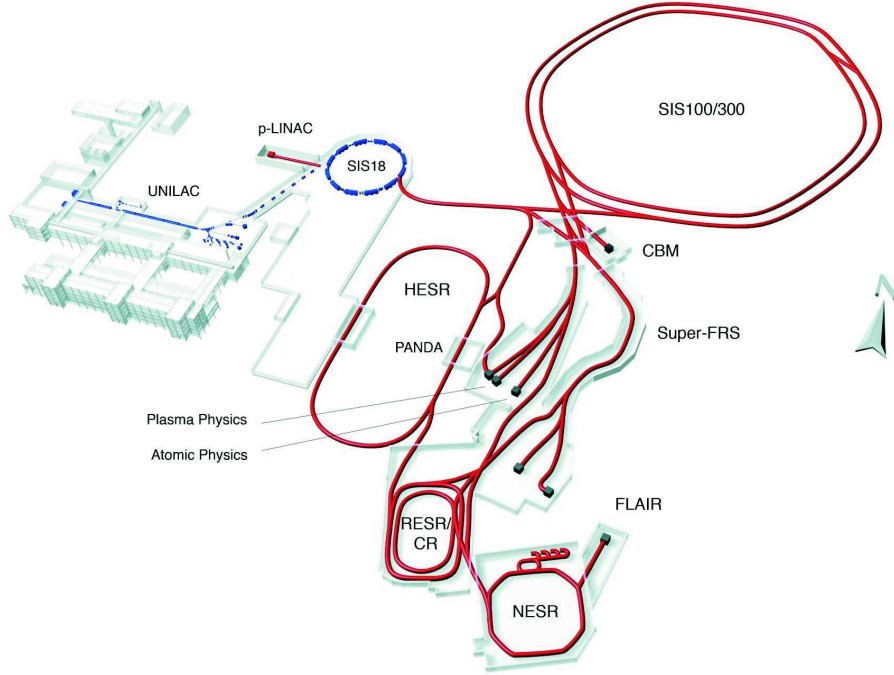
**Figure 5.** Schematic of the future facility for antiproton and ion research (FAIR) at GSI.

of radioactive nuclides can be polarized with high efficiency. The detection of the asymmetry of beta decay, for example, will allow one to explore the vector/axial-vector (VA)-structure of the weak interaction and to set limits for the masses of heavy bosons, which are not included in the Standard Model.

Direct mass measurements on unstable nuclides with ultra-high accuracy up to $\delta m/m \approx 10^{-11}$ are another class of investigations which become possible at the HITRAP facility at FLAIR. Such an accuracy would allow one to determine the 1s-Lamb shift of $U^{91+}$ with an accuracy of $\delta mc^2 \approx 2eV$, better than presently possible by X-ray spectroscopy [43]. If the QED calculations are found to be correct, nuclear charge radii also of unstable nuclides can be determined. For a general exploration of the nuclear mass surface in the chart of nuclei an accuracy in the mass determination of $\delta m/m \approx 10^{-6}$ to $10^{-7}$ is in general sufficient as planned by isochronous or Schottky mass spectrometry experiments at the NESR storage ring. However, in some cases, like double-beta decay or tests of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, a much higher accuracy is required, which is possible by use of HCI stored in a Penning trap at HITRAP [34] and at MATS [5].

*3.2. Facility for Low-Energy Antiproton and Ion Research (FLAIR)*
The planned FLAIR facility will be the most intense source of low-energy antiprotons world-wide [44]. The beam intensity of extracted low-energy antiprotons will be two orders of magnitude higher in the FLAIR facility compared to the Antiproton Decelerator (AD) at CERN. Hence we anticipate that experiments with trapped antiprotons will be performed at the FLAIR facility, which are currently impossible anywhere else due to intensity reasons. A possible highlight in the field of low-energy antimatter research would be the first direct experimental investigation of the gravitational interaction of antimatter which has never been attempted up to now. Such investigations could be performed on ultra-cold antihydrogen atoms [45] which are produced by recombining trapped antiprotons with positrons in a so-called nested Penning trap. The effect of

gravity on antimatter is an important issue for the development of quantum theories of gravity.

## Acknowledgments

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